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ARE THERE ROTATION MEASURE GRADIENTS ACROSS ACTIVE GALACTIC NUCLEI JETS?

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ABSTRACT

We report on multi-frequency polarimetry very long baseline interferometry observations of active galactic nuclei using the Very Long Baseline Array. These observations are used to construct images of the Faraday rotation measure (RM) in J1613+342, Mrk 501, 3C 371, and BL Lac. Despite having resolved the jets in total intensity and polarization for three of these sources no RM gradients are found. This is in contrast to the large fraction of sources with RM gradients now claimed in the literature and invoked as evidence in support of helical magnetic fields. We propose objective criteria for establishing what constitutes an RM gradient. Furthermore, although we note the absence of simple, monotonic gradients, comparison with simulations could reveal systematic changes in the RM that may be masked by a varying jet orientation.

Key words: galaxies: active – galaxies: individual (3C 371, Mrk 501, J1613+342, BL Lac) – radio continuum: galaxies

1. INTRODUCTION

Understanding how the jets from active galactic nuclei (AGNs) are launched is an outstanding question in astrophysics. Blandford & Znajek (1977) proposed an electromagnetic model by which the energy of the black hole could launch a relativistic jet. Magnetic fields play an important role in this and many of the proposed models and simulations (e.g., Meier et al. 2001, Meier 2005). A predicted consequence of strong, ordered magnetic fields that wrap around the jet is a gradient in the Faraday rotation measure (RM) transverse to the long axis of the jet (Blandford 1993). Asada et al. (2002) and Zavala & Taylor (2005) found evidence for RM gradients in 3C 273, and this was quickly followed with claims for RM gradients in 0745+241, 0820+225, Mrk 501, and 3C 371 by Gabuzda et al. (2004), and in DA 237 and 1156+295, 1749+096 by Gabuzda et al. (2008). Recently, Contopoulos et al. (2009) claim that RM gradients have been established in 36 instances in 29 sources and further suggest that the sense of RM gradients has a preferred direction. They claim that the preponderance of clockwise gradients (22) over counterclockwise (14) gradients is the result of an invariant twist of the magnetic fields in AGN jets. Note, however, that Königl (2010) shows that if such a preference exists, it can be explained in terms of standard models.

Considering the observational results, one is left with the impression that transverse RM gradients on parsec scales are the rule rather than the exception. The best-established (spatially resolved) case is still that in 3C 273, which is an exceptionally nearby quasar and one of the brightest radio sources in the sky at centimeter wavelengths. With the exception of 3C 273, many of the transverse RM gradients claimed in the literature are in sources, where the synthesized beam spans not much more than the width of the jet (e.g., Gabuzda et al. 2004). Increasing the angular resolution by going to shorter wavelengths is seldom rewarding, as the jets are steep-spectrum sources, so at shorter wavelengths one tends to probe only the brightest part of the jet base. Observers thus run the risk of extrapolating results from a nearby, well-resolved object onto a less well-resolved population. A further difficulty is that the observations require a broad coverage in wavelength-squared space, obtained simultaneously, with matching resolution. This wavelength coverage is not always achieved in Very Long Baseline Interferometry (VLBI) polarization observations.

The considerable body of observational literature describing RM features on parsec scales begs for support from simulations. Given a relativistic jet pointed close to the line of sight with a dominantly toroidal magnetic field component that extends into a Faraday rotating plasma, what should observers see? Broderick & McKinney (2010) have recently completed such an effort. Their results show that jets that are not well resolved will not produce simple transverse RM gradients. Broderick & McKinney also verify the observational intuition that spectral index effects will significantly complicate the interpretation of RM gradients in optically thick regions. They also provide a physical connection between the black hole and the RM via the accretion rate.

We examine transverse RM gradients in relativistic jets which maximize the spatial resolution at our disposal by selecting a sample of four strong, broad jets from the MOJAVE sample (Lister et al. 2009) known to be well polarized at centimeter wavelengths. We then carried out sensitive multi-band VLBI polarimetry on them. We present these observations and note the presence or absence of transverse RM gradients. We conclude with a set of objective observational criteria for determining if a transverse RM gradient exists.

We assume $H_0 = 71$ km s^{-1} Mpc^{-1} and a ΛCDM cosmology with $\Omega_\lambda = 0.7$ and $\Omega_m = 0.3$ (e.g., Eisenstein et al. 2005; Hinshaw et al. 2009).

2. OBSERVATIONS AND DATA REDUCTION

The observations were carried out at 8, 13, and 15 GHz on 2003 September 26 using all 10 elements of the Very Long Baseline Array (VLBA) of NRAO. Each source was observed in ∼12 scans of 2–3 minutes each at each frequency band. Amplitude calibration for each antenna was derived from measurements of antenna gain and system temperatures during each run. Delays between the stations' clocks were determined using the AIPS task FRING (Schwab & Cotton 1983). Calibration was applied by splitting the multi-source data set immediately prior

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14. ABSTRACT
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15. SUBJECT TERMS

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to preliminary editing, imaging (using natural weighting), deconvolution (using the CLEAN algorithm), and self-calibration in Difmap (Shepherd et al. 1995). The preliminary models developed in Difmap were subsequently applied in AIPS to make phase corrections, to determine the leakage terms between the right-circular polarization and left-circular polarization feeds and to correct for residual phase differences between polarizations. Total intensity images were made using all available frequencies in 8, 13, or 15 GHz bands, while Stokes Q and U images were constructed at 8.114, 8.209, 8.369, 8.594, 12.915, 13.885, 14.915, and 15.391 GHz with 8 MHz bandwidths. Further subdivision of the frequencies within the 8 MHz bandwidths was deemed unnecessary given the maximum RMs observed. Absolute calibration of the polarization angle was accomplished by observations of 3C279, 1751+096, and BL Lac, which are observed regularly by the Very Large Array polarization monitoring program[4] to provide calibration information for VLBA users. RM maps were then formed from matched resolution polarization angle images at these eight frequencies. Resolutions were matched by applying the appropriate taper in the (u, v) plane when imaging and then restoring with a common beam size. Pixels in the RM images were blanked if the error in any polarization angle image exceeded 20°, or if the total intensity was less than six times the rms noise level. No correction for redshift has been made, so the intrinsic RMs in the rest frame of the source are larger than the observed values by $(1 + z)^2$.

3. RESULTS

For each source, we examined the RM image and took slices across the jet. Outside of the core region, the RMs are well fit by a λ^2-law fit, and have constant fractional polarization, which taken together indicate that their origin is most likely in an external Faraday screen, and not due to thermal material intermixed with the radiating plasma (Burn 1966). In the core region, some large deviations from a λ^2-law may be present due to unresolved substructures. For one source (3C 371), RMs could only be determined at the base of the jet where the jet is only marginally resolved. For the other three sources, we were able to resolve the jet and we present the RM images obtained.

3.1. J1613+3412

This source is a flat spectrum radio quasar with a redshift of $z = 1.401$ (Burbidge 1970). It emits powerfully across the electromagnetic spectrum and is detected in the gamma rays by EGRET (Hartman et al. 1999). It is detected by *Fermi* with a flux of 0.5 $\times 10^{-9}$ (100 MeV to 100 GeV) photons cm^{-2} s^{-1} (Abdo et al. 2010). It is a known superluminal source (Piner & Kingham 1997; Lister et al. 2009), with apparent velocities between 9 and 15 c. A compact, flat spectrum core is identified with a steep spectrum jet extending to the south. This jet is exceptionally broad, with an opening angle of ∼60°. Piner & Kingham (1997) estimate the orientation of the jet at <7° to the line of sight.

In Figure 1, we show the RM image for J1613+3412 with an inset slice across the jet at its broadest point. The jet is ∼6 mas wide or about 5 beams across, so well resolved. We find a Spearman correlation coefficient of −0.2, and a reduced χ^2 for a linear fit of 2.8, which reject a linear gradient across the jet. There is a sharp change in the RM along the jet from relatively high values in the core of −600 rad m^{-2} decreasing to an average

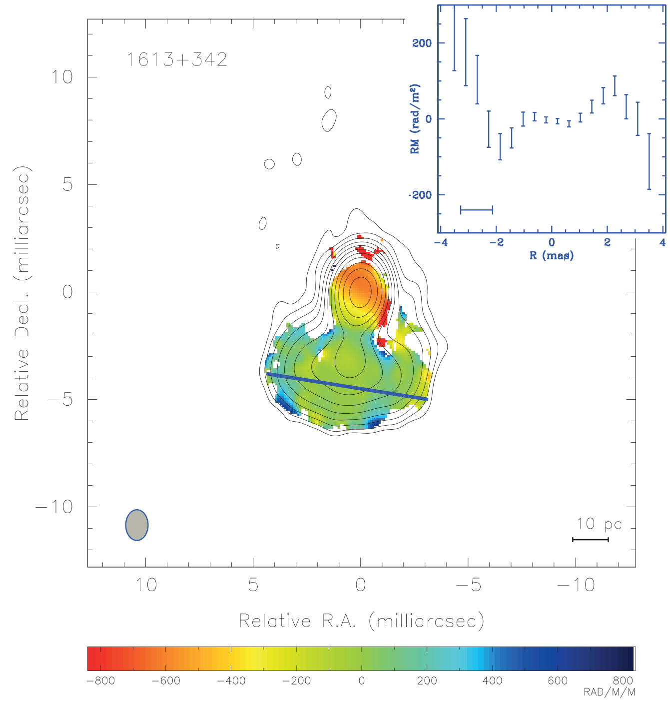

Figure 1. Rotation Measure image of J1613+342 in false color with a slice perpendicular to the jet axis inset. The zero point on the inset slice corresponds to the center of the jet, and the bar denotes the angular resolution. Image coordinates are only relative since no phase referencing was performed. The synthesized beam (shown in lower left) has dimensions 1.6 × 1.2 mas in position angle 0°. Contours are drawn from the 8 GHz total intensity image logarithmically at factor of two intervals with the first contour at 2 mJy beam^{-1}. The Spearman correlation coefficient is −0.2, and the reduced χ^2 for a linear fit of the RM with position is 2.8.

of 0 rad m^{-2} in the outer part of the jet (Spearman correlation, −0.83). This behavior is typical for blazars, which have much higher RMs in their central regions, presumably because of the increase in density near the bottom of the gravitational potential of the supermassive black hole (Zavala & Taylor 2002, 2003, 2004). The RM image from Zavala & Taylor (2003) is quite similar, though it does not cover as much of the jet.

3.2. Mrk 501

Mrk 501 is a well-studied BL Lac object at $z = 0.0337$ (Ulrich et al. 1975). It also emits across the electromagnetic spectrum, and was one of the first sources detected at TeV energies (Quinn et al. 1996). It is detected by *Fermi* with a flux of 8.3 $\times 10^{-9}$ (100 MeV to 100 GeV) photons cm^{-2} s^{-1} (Abdo et al. 2010). VLBI observations have revealed a limb-brightened structure, possibly the result of a dual velocity structure (Giroletti et al. 2004, 2008). Giroletti et al. (2008) find a well-ordered magnetic field structure in the outer jet (100 mas from the core) suggesting that the RM in this region is low and uniform. The maximum jet speed in the MOJAVE archive is 0.2c (Lister et al. 2009), though Piner et al. (2009) report a speed of 3.3 ± 0.3 c using higher resolution 43 GHz observations. In Figure 2, we show the RM image for Mrk 501 with an inset slice across the jet at its broadest point where the RMs are well determined, roughly 10 mas from the core. The jet is ∼8 mas wide or about 6 beams across, so well resolved, although the detection of polarized flux is restricted to the brighter ∼75% of the jet. The slice across the jet shows some variations between 0 and 200 rad m^{-2}, but

[4] http://www.aoc.nrao.edu/∼smyers/calibration/

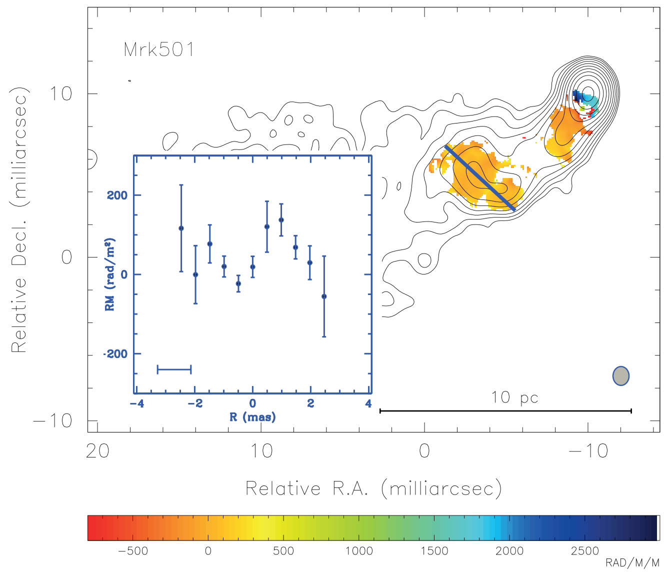

Figure 2. Rotation Measure image of Mrk 501 in false color with a slice perpendicular to the jet axis inset. The synthesized beam has dimensions 1.4 × 1.2 mas in position angle 0°. Contours are drawn starting at 1 mJy beam^{-1}. The Spearman correlation coefficient is −0.1 and the reduced χ^2 for a linear fit is 2.0.

no gradient (Spearman correlation coefficient is −0.1, and the reduced χ^2 for a linear fit is 2.0). Gabuzda et al. (2004) claim a gradient from -63 ± 30 to $+130 \pm 20$ rad m^{-2} at a location somewhat closer to the core than the slice shown in Figure 2. The RM determination of Gabuzda et al. was based on three observations of the polarization angle taken at 5, 8, and 15 GHz in 1997 using the standard frequency bands. Their resolution was somewhat lower (beam 2.55 × 1.89 mas in position angle −24°). Croke et al. (2010) report a transverse RM gradient based on 1.6 to 8.5 GHz VLBA observations. According to their spectral index maps, the location where the RM gradient is detected is relatively flat.

We see a clear change in RM along the jet from relatively high values in the core of 2000 rad m^{-2} decreasing to an average of 10 rad m^{-2}. In the core region, there are large and abrupt changes in the RM, however we caution against interpreting this as an RM gradient since substructure in the core is likely. Furthermore, the local jet direction is not always well defined and one can find abrupt changes in RM in essentially every orientation in the cores of AGNs.

3.3. 3C 371

3C 371 is a high-power BL Lac object at a redshift of 0.051 (Lawrence et al. 1996). The radio jet has been well studied on the parsec scale by Gómez & Marscher (2000) and they suggest a classification as a transition object between a BL Lac and a radio galaxy. 3C 371 is detected by *Fermi* with a flux of 1.9×10^{-9} (100 MeV to 100 GeV) photons cm^{-2} s^{-1} (Abdo et al. 2010). The jet is relatively slow moving (0.1 c; Lister et al. 2009) and taking into account the many MOJAVE epochs and two epochs of Gómez & Marscher (2000) is consistently weakly polarized. The kiloparsec scale jet has been detected in the radio (Cassaro et al. 1999), optical (Scarpa et al. 1999), and in X-rays (Pesce et al. 2001). Taken together these results suggest an object with radio galaxy like properties (Zensus 1997), although variability undoubtedly plays a role. Of the four sources in this work, 3C 371 may have the jet with the largest angle to the line of sight of ≈20° (Gómez & Marscher 2000).

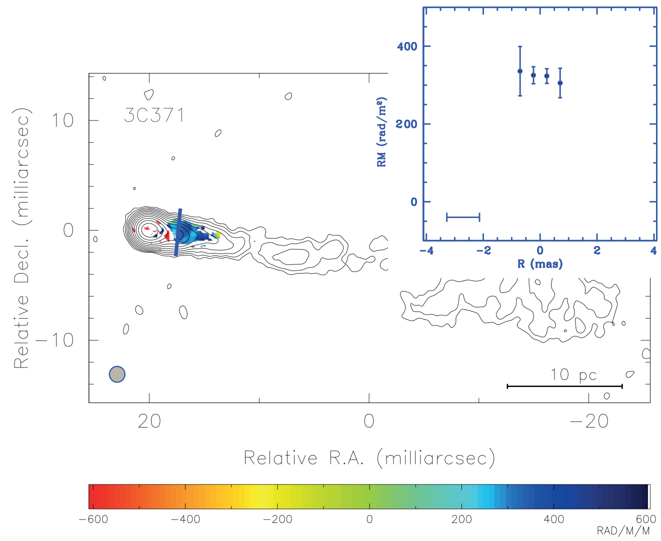

Figure 3. Rotation Measure image of 3C 371 in false color with a slice perpendicular to the jet axis inset. The synthesized beam has dimensions 1.25 × 1.25 mas. Contours are drawn starting at 1 mJy beam^{-1}. There is insufficient data to compute the Spearman correlation coefficient or the χ^2 for a linear fit.

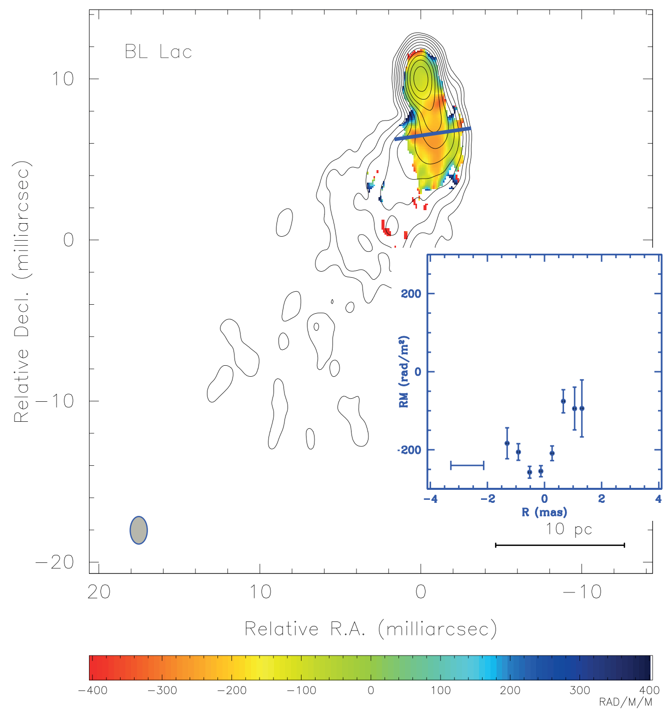

Figure 4. Rotation Measure image of BL Lac in false color with a slice perpendicular to the jet axis inset. The synthesized beam has dimensions 1.7 × 1.0 mas in position angle 0°. Contours are drawn starting at 1 mJy beam^{-1}. The Spearman correlation coefficient is 0.5 and the reduced χ^2 for a linear fit is 5.7.

In Figure 3, we show the RM image for 3C 371 with an inset slice across the region, where the RMs cover the largest extent. The jet, however, is not resolved so we can say little about RM gradients in this object. Further out the jet is well resolved in total intensity, but is not detected in linear polarization.

3.4. BL Lac

The archetype of its class (Strittmatter et al. 1972), BL Lac is at $z = 0.0686$ (Vermeulen et al. 1995) and well known for its optical variability and powerful emission across the electromagnetic spectrum (Bregman et al. 1990), including

γ-rays (Bloom et al. 1997). The compact structure of BL Lac has been studied extensively with VLBI polarimetry by Denn et al. (2000), who found that highly polarized components were ejected from the core and moved away on helical trajectories. BL Lac is also a known superluminal source with velocities of 3.5 c (Mutel et al. 1990) to as high as 10 c, with a jet closely aligned to the line of sight (Jorstad et al. 2005).

In Figure 4, we show the RM image for BL Lac with an inset slice across the jet at its broadest point, where the RMs are well determined, roughly 5 mas from the core. The jet is $\sim$4 mas wide or about 3 beams across, so resolved. The slice across the jet shows lower RMs at the edges of the jet and an RM of -250 in the center. The error in the RMs at the edge of the jet are large and there are clearly some values along the edge at low signal-to-noise ratio that should not be trusted. The RMs in the core are low (-70 ± 10 rad m^{-2}), which is a bit unusual for AGNs, but we could just be catching BL Lac in a low state. Zavala & Taylor (2003) found an RM of -380 rad m^{-2}, and before that Reynolds et al. (2001) found a core RM of -550 rad m^{-2}.

4. DISCUSSION

Contopoulos et al. (2009) claim to have found 29 AGNs from the literature that have RM gradients transverse to the jet direction that are monotonic and "extend across all or nearly all of the jet." Contopoulos et al. do not present any statistics on how well fit the gradients are by a straight line. This list includes both Mrk 501 and 3C 371 studied here. The observations of Gabuzda et al. (2004) use three frequencies, which is essentially the minimum with which to claim an RM determination, and the observations (with the possible exception of Mrk 501) do not significantly resolve the region in which the RM is detected. For example, approximately one synthesized beamwidth spans the RM extent of 3C 371 in Figures 1 and 2 of Gabuzda et al. (2004). Contopoulos et al. (2009) also claim the presence of RM gradients in B0212+735 and B1803+784 based on the observations of Zavala & Taylor (2003). In both of these instances, the jets were not resolved and it appears that spurious values at edge pixels (a common problem in determinations of RMs in regions of low signal-to-noise) were overinterpreted to indicate the presence of a gradient.

Contopoulos et al. list 7/29 sources with RM gradients at a distance of 0 mas and thus coincident with the VLBI core. As the simulations of Broderick & McKinney (2010) show this is a problematic area for RM measurements. High spatial resolution polarimetry observations reveal the complex nature of these regions and further justify caution in claiming detection of RM gradients at the "core" of AGNs (Zavala & Taylor 2001; Denn et al. 2000).

If one only has two measurements then a gradient will exist anytime these values differ. We suggest that to establish an RM gradient requires that the following two observational and two physical constraints are met.

1. At least three resolution elements across the jet.
2. A change in the RM by at least three times the typical error.
3. An optically thin synchrotron spectrum at the location of the gradient.
4. A monotonically smooth (within the errors) change in the RM from side to side.

To date the above criteria have been met (to our knowledge) only for 3C 273. In this work, we attempt to improve our observational footing by applying these criteria to four additional sources. While 3C 371 fails on the first (observational) test, the other three sources pass the first two observational criteria, and the third physical criterion of an optically thin jet, but fail on the critical fourth physical criterion. That is, these three sources have data of sufficient quality that they could reveal an RM gradient, but no smooth monotonic gradient across the jet is found. However, even if simple monotonic gradients across AGN jets turn out to be rare, it is still important to make careful comparison of the observed RM profiles with simulations. For example, the inset slice in our Figure 1 bears some resemblance to Figure 5(a) of Broderick & McKinney (2010). In their simulation, the jet is oriented at 10° to the line of sight, which is very close to the estimate of 7° (Piner & Kingham 1997).

It is worth noting in passing that all of the sources studied here are detected in γ-rays. This is also true for 3C 273. This may be the result of the selection criteria of broad jets, together with the fact that sources with broad jets tend to be preferentially detected at high energies (Taylor et al. 2007; Linford et al. 2010).

5. CONCLUSIONS

Based on well-resolved RM imaging of three AGNs, we find that none of them exhibit a monotonic linear gradient in the RM across the jet. Examination of claims for RM gradients in the literature (including two of the four sources we observed) are found to be based on observations that generally have not resolved the jet, include components with large opacities, or suffer from spurious edge effects. We offer a set of criteria that can be used to reliably determine if an RM gradient exists. Moreover, even if simple linear gradients across AGN jets turn out to be rare, it will be important to make careful comparison of the observed RM profiles with simulations (e.g., Broderick & McKinney 2010). Future observations with higher resolution, such as will be afforded by VSOP-2, will be crucial in order to increase the number of parsec-scale jets that are well resolved across the jet. New wideband correlators will allow for RM synthesis (Brentjens & de Bruyn 2005) observations with increased precision and the ability to disentangle multiple RM screens. Another possibility, assuming improvements in the sensitivity of VLBI arrays, is the detection of polarization in two-sided jet sources such as NGC 1052 (Vermeulen et al. 2003) or 3C 84 (Taylor et al. 2006). Polarized counterjets may reveal RM gradients consistent with a dominant toroidal field (Blandford 1993).

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Facility: VLBA()

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